Variations of the NGST Yardstick Design

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Abstract

We have investigated the sensitivity of the NGST GSFC Yardstick Design to variations of its principal design parameters (mirror diameter, mirror reflectivity, sunshield temperature, detector noise, detector field of view, *etc.*) The investigation utilized the NGST Mission Simulator (NMS), which incorporates a physical model of the Yardstick Design, an exposure time calculator, and an observation scheduler. The NMS computes the duration of the NGST mission for the observations in the Ad Hoc Science Working Group Design Reference Mission (ASWG DRM) and a given mission architecture. By varying the design parameters about their baseline values the sensitivity of the mission duration to those parameters was measured. We also investigated, for the 2.9-yr ASWG DRM, the reduction of observatory size that can be gained with inclined, or large elliptical solar orbits.

Yardstick Model

To compute the duration of the NGST mission, the time required to conduct each observation in the reference science program is computed. The observation time is comprised of the exposure time and associated overheads, both of which are functions of the observatory design, the observation characteristics (target direction, brightness, diameter, and required number; S/N; and wavelength and spectral resolution), and background sources.

The NGST is comprised of an Optical Telescope Assembly, a sunshield, and an Integrated Science Instrument Module. The NGST Mission Simulator (NMS) models the signal for an observation in terms of the throughput and internal backgrounds of NGST. The sources of internal background are detector readout noise and dark current, OTA thermal emission, and sunshield emission scattered by the OTA. The most significant source of external background, Zodiacal Light, is modeled in the NMS by a 3-D dust distribution.

A statistical summary of the observations in the Ad Hoc Science Working Group reference science program is given in Table 1. The wavelength dependence of the components comprising the system throughput and backgrounds are shown in Figures 1 and 2 (respectively). The values of the parameters of the Yardstick design are given in Table 2.

Table 1: Mission Duration for Yardstick Design and ASWG DRM

Configuration	Duration [years]	Percentage of Mission	Exp.Time [years]	Exposure Efficiency
NIR-ACCUM	0.64	22%	0.49	76%
NIR-SPEC	0.63	22%	0.53	84%
OPT-ACCUM	0.56	19%	0.38	68%
MIR-ACCUM	0.59	20%	0.40	68%
MIR-SPEC	0.50	17%	0.46	92%
TOTAL	2.93	100%	2.27	77%

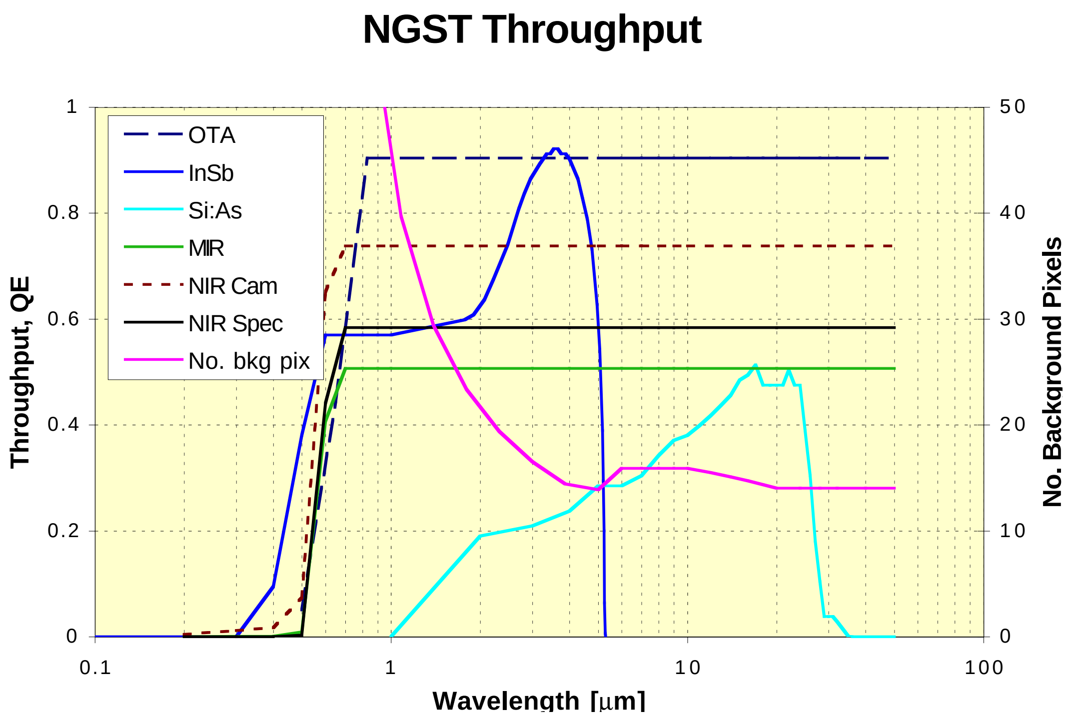


Fig. 1: The OTA and ISIM throughput, detector quantum efficiency, and the effective number of background pixels (inverse sharpness) for a point source.

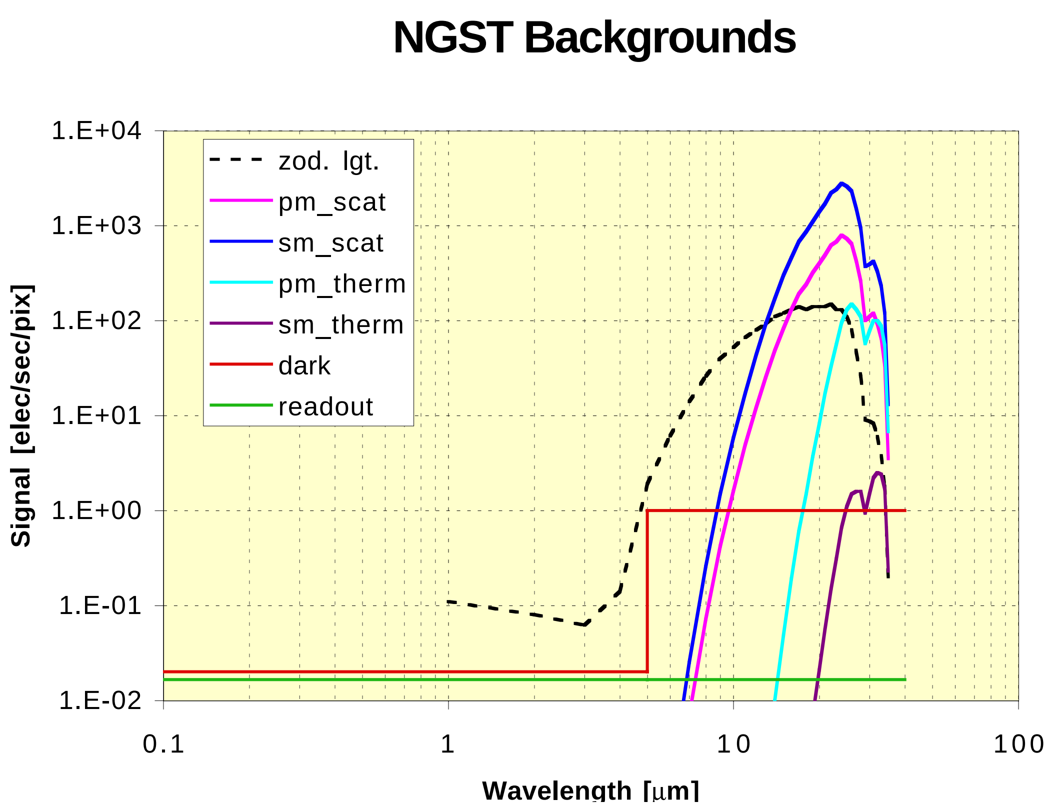


Fig. 2: The signal is the detector output, which is proportional to the product of the optical throughput and detector QE for the external components (ZL, sunshield, and mirror emission.) The bandwidth is 20% for the external signals.

Table 2: Yardstick Design Parameters	
Value	**Parameter**
Spacecraft and OTA	
8.00	Diameter, primary [m]
0.90	Diameter, secondary [m]
10.0	Focal length, primary mirror [m]
8.9	Primary to secondary separation [m]
0.03	Frontside emissivity, primary and secondary
0.03	Backside emissivity, primary mirror
0.70	Backside emissivity, secondary mirror
40.0	Temperature, primary [K]
30.0	Temperature secondary [K]
100.0	Temperature, sunshield backside [K]
266.2	Sunshield area [m^2]
7.5	Separation from primary frontside [m]
4.3	Separation from primary backside [m]
8.5	Separation from secondary [m]
0.03	Sunshield emissivity
0.01	Dust coverage fraction, primary and secondary mirrors
0.001	BRDF, primary (typical)
0.003	BRDF, secondary (typical)
85.0	Sun-LOS angle, minimum [˚]
135.0	Sun-LOS angle, maximum [˚]
Detectors	
InSb	Detector name
27.0	Pixel size [µm]
0.02	Dark current [e^-/sec]
4	Read-out noise per read, r.m.s. [e^-]
960	Maximum integration time (Cosmic Ray time) [sec]
60,000.	Well depth [e^-]
Si:As	Detector name
27.0	Pixel size [µm]
1	Dark current [e^-]/sec]
4	Read-out noise per read, r.m.s. [e^-]
960	Maximum integration time (Cosmic Ray time) [sec]
60,000.	Well depth [e^-]

Value	Parameter
Science Instrument Modules	
NIR-ACCUM	Configuration name
InSb	Detector
gold4_filt	Transmission(λ)
8192	FOV ≡ Length of side [pixels]
4	Sky View [arcmin per side]
0.	Multiplex factor
5.0	Readout time, per pixel, [μsec]
1,048,576	Number of pixels per MUX/amplifier
32	Effective number (for overhead) of Fowler samples
NIR-SPEC	Configuration name
InSb	Detector
gold9_grat	Transmission(λ)
4096	FOV ≡ Length of side [pixels]
3	Sky View [arcmin per side]
1000	Multiplex factor
5.0	Readout time, per pixel, [μsec]
1,048,576	Number of pixels per MUX/amplifier
32	Effective number (for overhead) of Fowler samples
OPT-ACCUM	Configuration name
InSb	Detector
gold4_filt	Transmission(λ)
8192	FOV ≡ Length of side [pixels]
4	Sky View [arcmin per side]
0.	Multiplex factor
5.0	Readout time, per pixel, [μsec]
1,048,576	Number of pixels per MUX/amp
32	Effective number (for overhead) of Fowler samples
MIR-ACCUM	Configuration name
Si:As	Detector
gold7_lens3_filt	Transmission(λ)
1024	FOV ≡ Length of side [pixels]
2	Sky View [arcmin per side]
0.	Multiplex factor
5.0	Readout time, per pixel, [μsec]
262,144	Number of pixels per MUX/amp
32	Effective number (for overhead) of Fowler samples

Value	Parameter
Science Instrument Modules	
MIR-SPEC	Configuration name
Si:As	Detector
gold7_lens3_grism	Transmission(λ)
1024	FOV ≡ Length of side [pixels]
2	Sky View [arcmin per side]
0.	Multiplex factor
5.0	Readout time, per pixel, [μsec]
262,144	Number of pixels per MUX/amp
32	Effective number (for overhead) of Fowler samples
Overheads	
60.0	Average major slew time [minutes]
15.0	Major slew settling time [minutes]
1.0	Average minor slew time [minutes]
1.0	Minor slew settling time [minutes]
5.0	Coarse tracker acquisition time [minutes]
5.0	Fine tracker acquisition time [minutes]
3.0	SI setup time, per ObsSet [minutes]
1.0	Spectral element setup time, [minutes]

Design Variations

We have employed the mission duration required to complete the ASWG DRM as the figure of merit for NGST designs. The NGST Yardstick Design can be analyzed in terms of its components contribution to minimizing the mission duration. To assess the importance, or optimization of a component, the variation of the mission duration (the Mission Elapsed Time = MET) can be determined as the parameter describing that component is varied. A global variation will reveal parameters that can be optimized by the MET reaching a minimum. Sensitive design parameters are those for which the MET varies sharply as the parameter is varied. This may be quantified in the vicinity of the baseline design by the slope $d\log(MET/MET_0)/d\log(p/p_0)$, where p represents a design parameter, and MET_0 and p_0 are the Yardstick values. Similarly, meta-variations involving the coordinated variation of several of the basic design parameters, described by a single, overall scale factor, can be studied.

The results of global, single-parameter variations are displayed graphically in Figures 3 – 14. In those figures, the Yardstick MET corresponds to that portion of the ASWG DRM affected by the particular parameter. For example, for OTA variations the full DRM is affected, for a variation specific to a single SI only observations with that SI are considered, and for detector variations only observations with that detector are considered.

The results of global, meta-variations for detector noise, detector size, and observatory size are presented graphically in Figure 15. For the detector noise variation, the dark current and readout effective noise current of all detectors are varied by the same scale factor. For the detector size variation, the detector length (in units of number of pixels) for all detectors is varied by a common scale factor. For the observatory size variation, the linear dimensions of the observatory are scaled homologously by a single scale factor, while retaining critical sampling of the point spread function.

The parametric sensitivity in the vicinity of the Yardstick design is presented in terms of the logarithmic derivative, $d\log(MET/MET_0)/d\log(p/p_0)$, in Table 3.

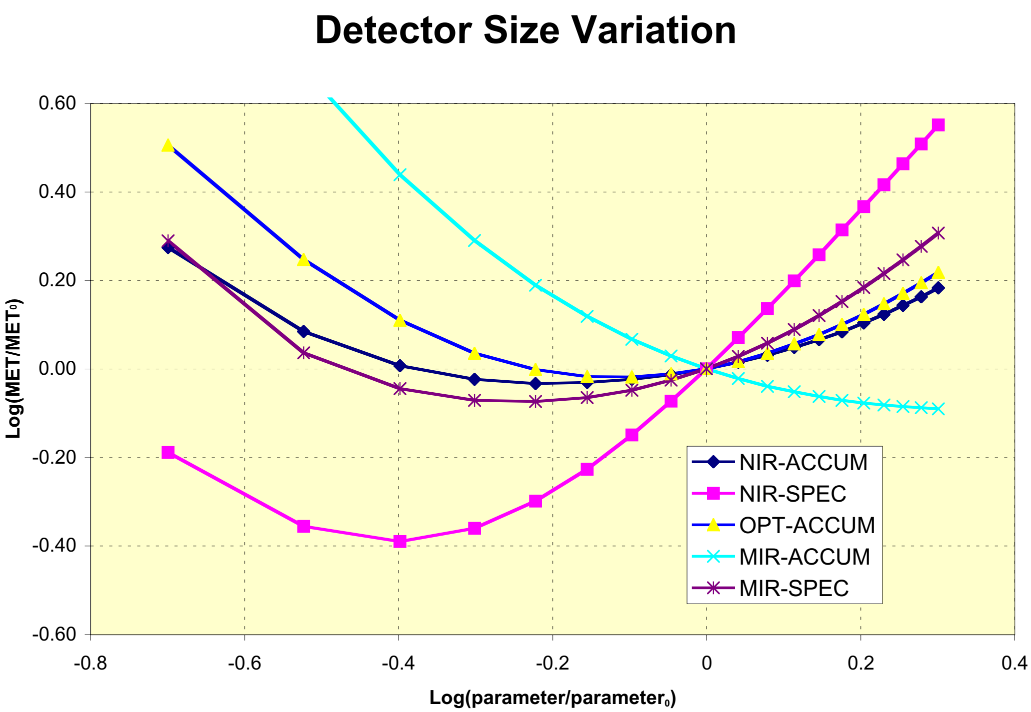


Fig. 3: Variation of the detector size, as given by the number of pixels per side. The physical size of a pixel and the number of MUX/amplifiers per detector are held constant. MET_0 is the duration of ASWG DRM observations utilizing each given SI.

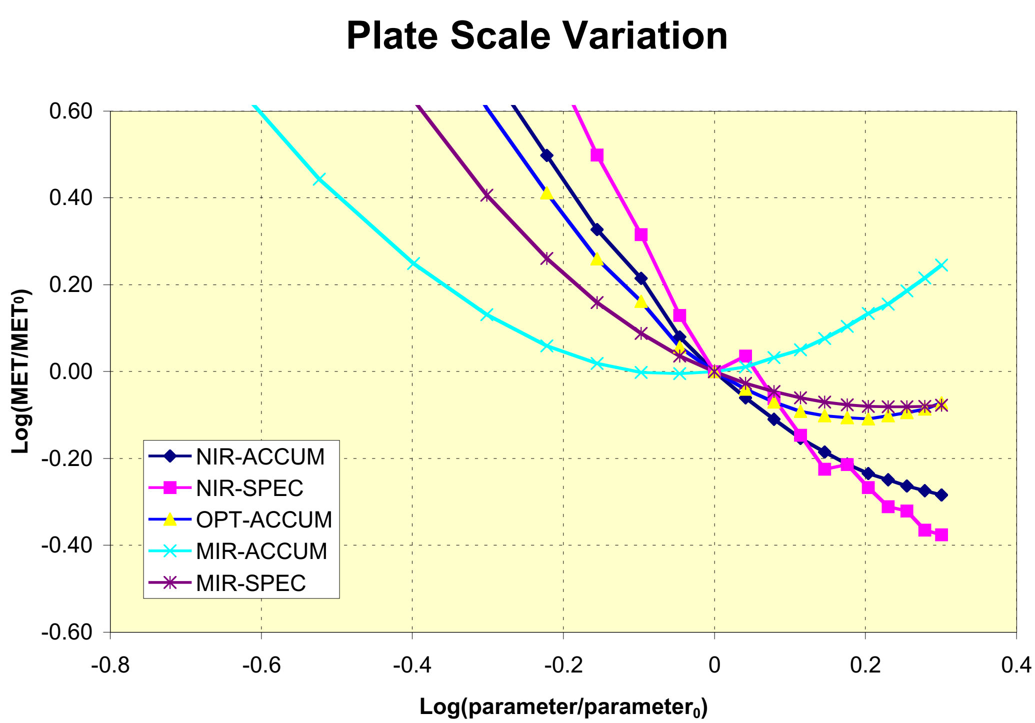


Fig. 4: Variation of the SI plate. MET_0 is the duration of ASWG DRM observations utilizing each given SI.

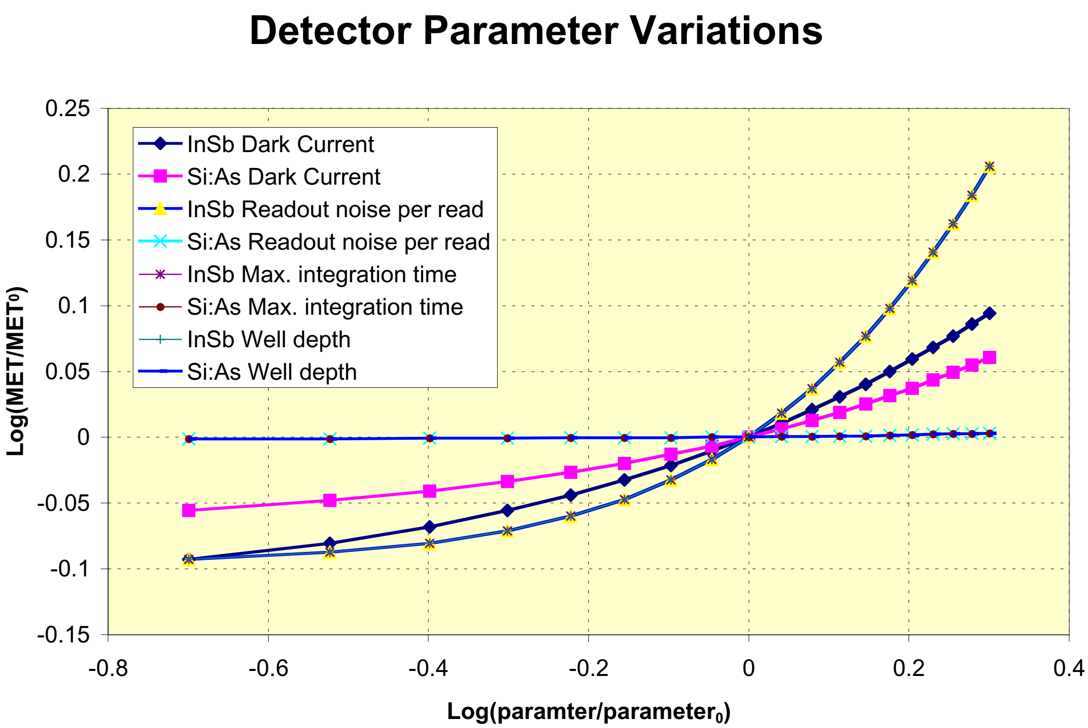


Fig. 5: Effect of detector characteristics. Greatest sensitivity is to InSb readout noise and cosmic ray time. Least is to Si:As readout noise and cosmic ray time. MET_0 refers to only observations with the given detector.

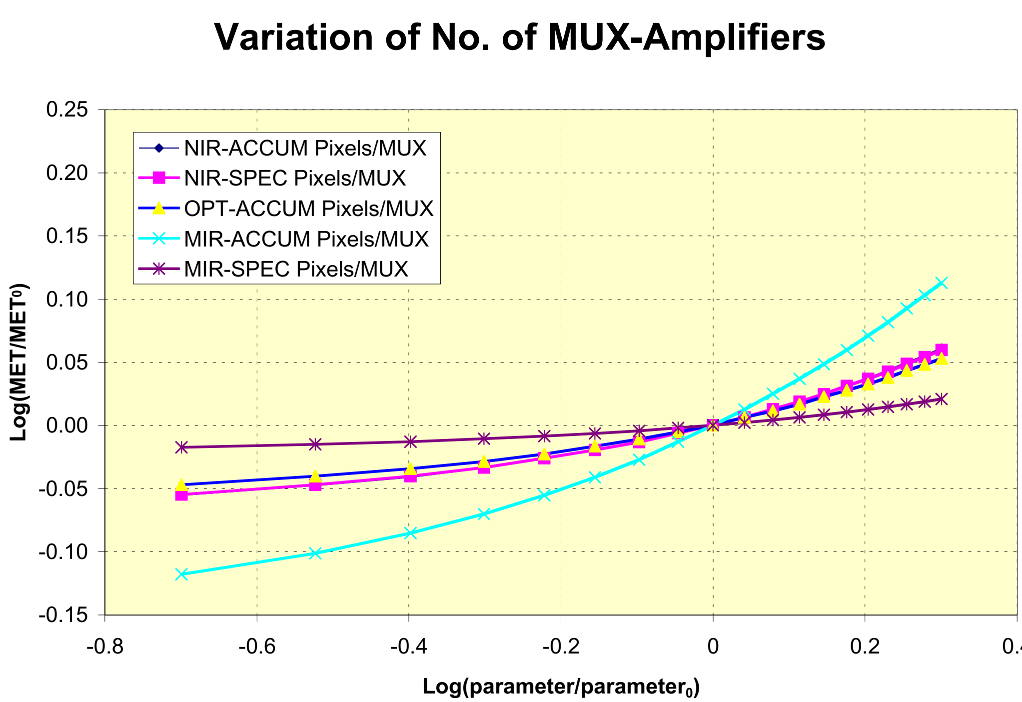


Fig. 6: Variation of the number of MUX/amplifiers. The variation in the inverse number, i.e., no. of detector pixels per MUX, is shown.

Detector Readout Time Variation

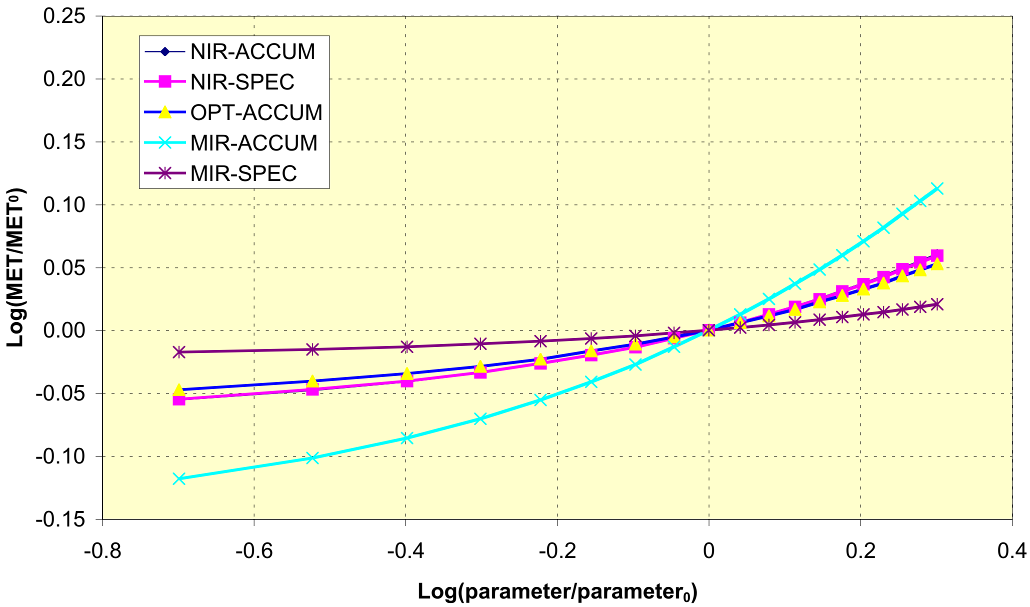


Fig. 7: Effect of readout speed, as measured by the time to read out a pixel. MIR images are most greatly affected.

No. Fowler Samples Variation

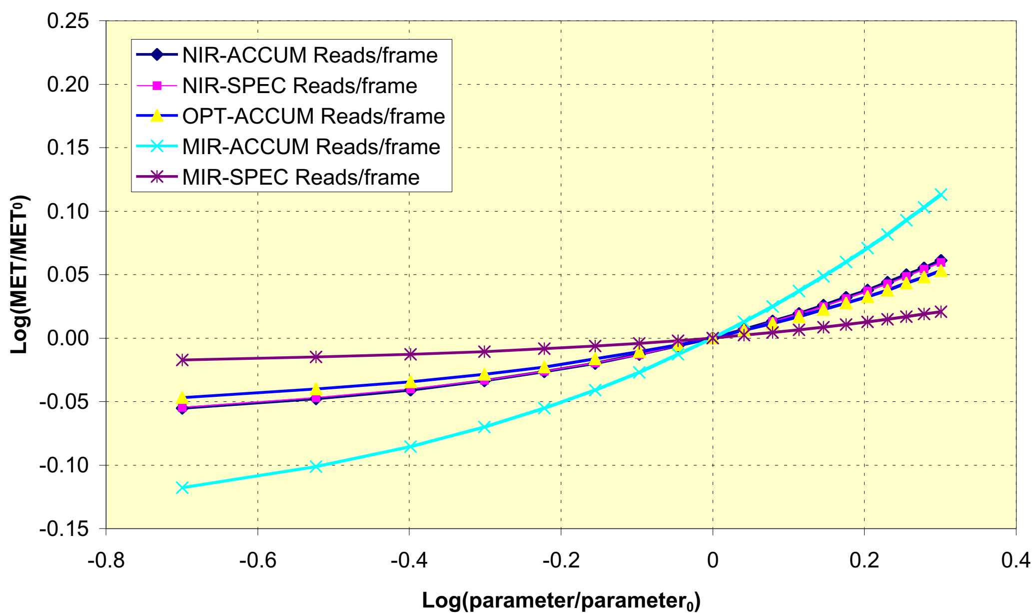


Fig. 8: Effect of the number of effective Fowler samples. MIR images are most greatly affected.

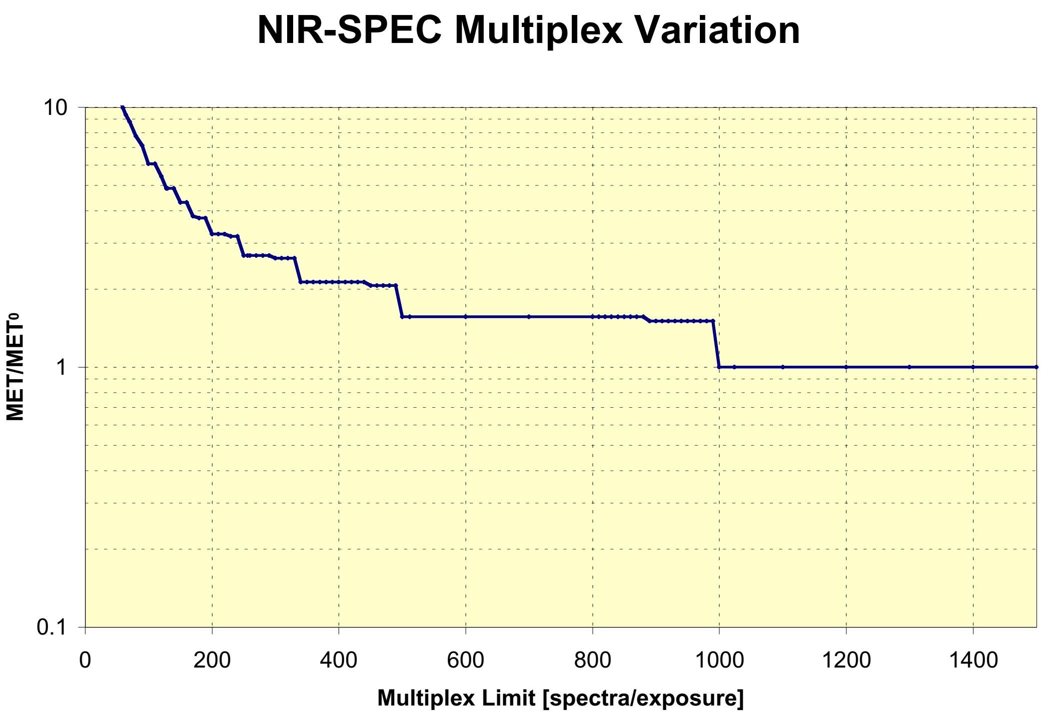
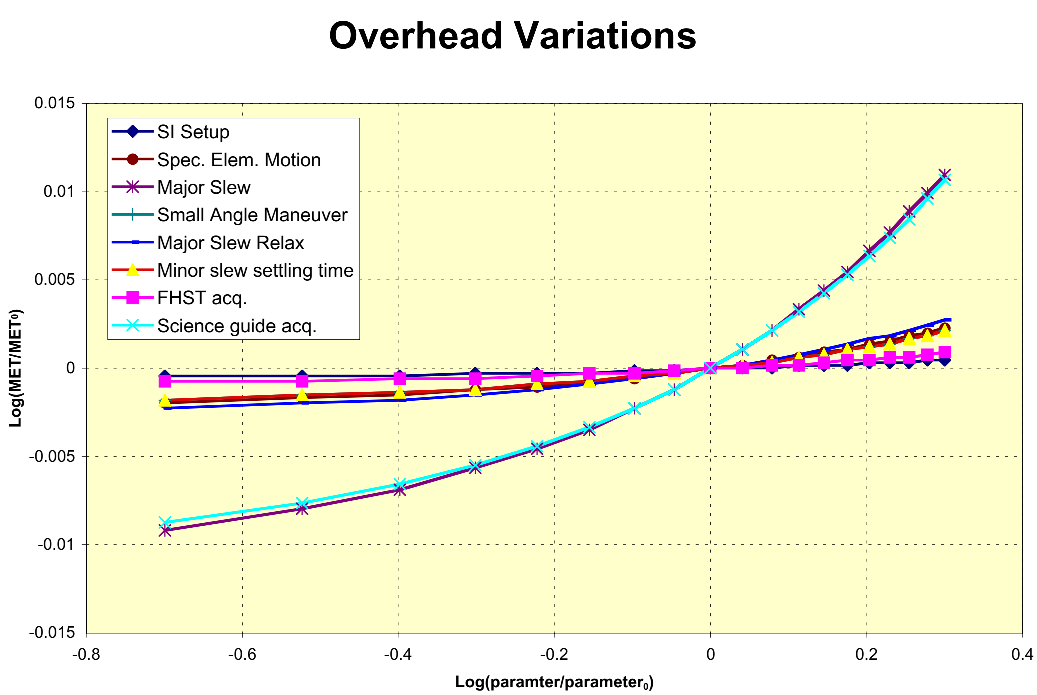


Fig. 9: The NIR-SPEC confusion limit on the number of spectra per image weakly affects the mission duration. The Yardstick limit is 1,000, which satisfies all ASWG DRM observations.

Fig. 10: Overheads have a small effect on the Yardstick Design + ASWG DRM. However, most important are slews between targets and science guide acquisition. See Figs. 5 - 8 for effects of readout overheads.



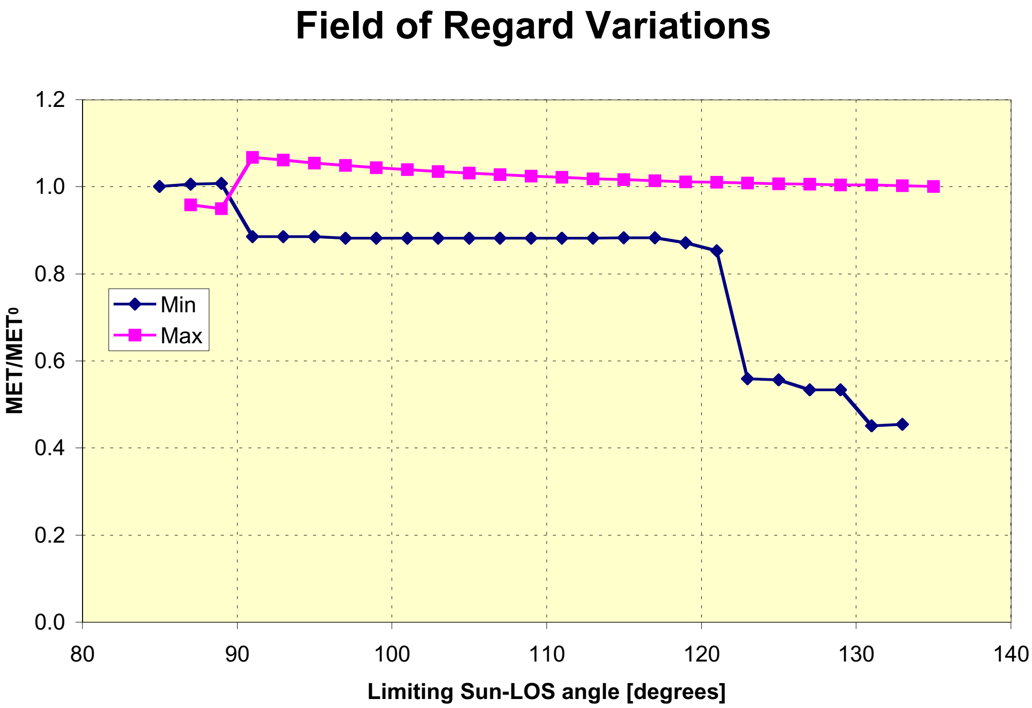


Fig. 11: During an observation, the angle between the LOS and the Sun must lie within an annulus (the field of regard, FOR) specified by minimum and maximum values of that angle. Over a wide range, the size of the FOR has little effect on MET, although CVZ targets will be lost if the minimum angle is greater than 90˚.

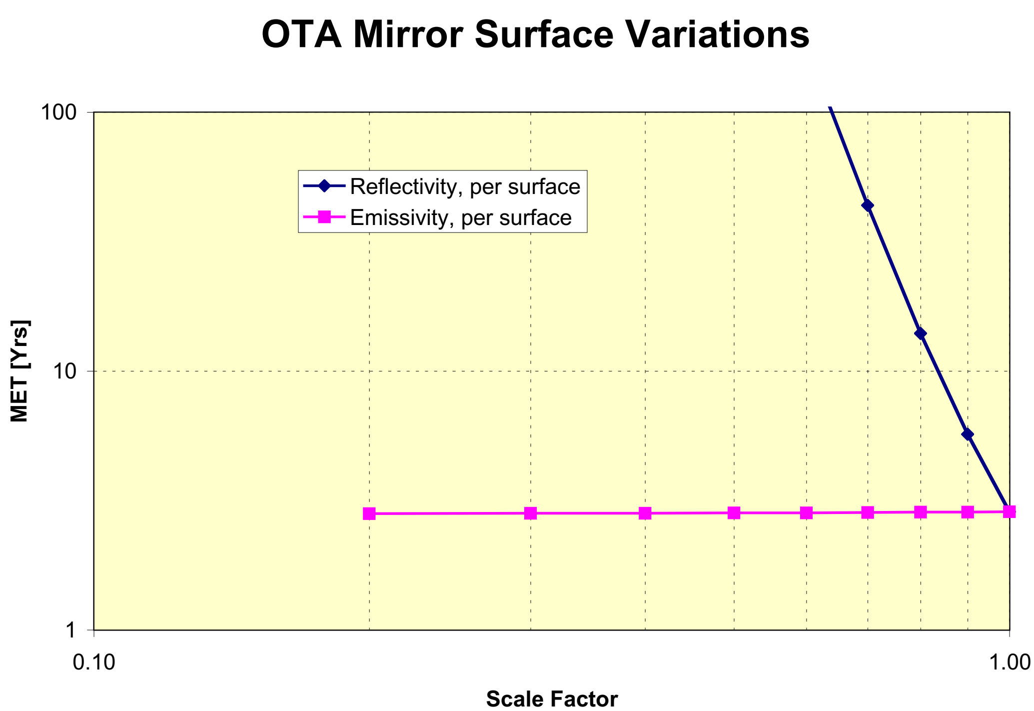


Fig. 12: Effects of mirror reflectivity and emissivity. These wavelength dependent functions are reduced by the reduced by the given factor, per surface. Note in Fig. 2 that mirror thermal emission is negligible, and so the variation of the emissivity has no effect.

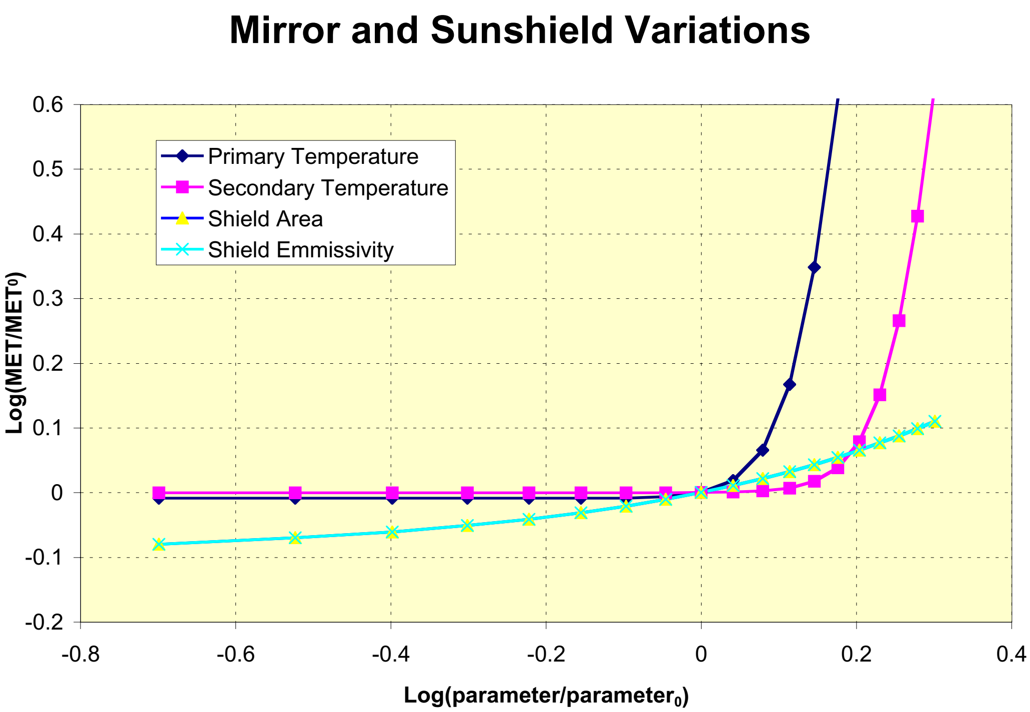


Fig. 13: Components affecting the MIR background. The full ASWG DRM contributes to MET. The sunshield affects the MIR background through the product of its area and emissivity.

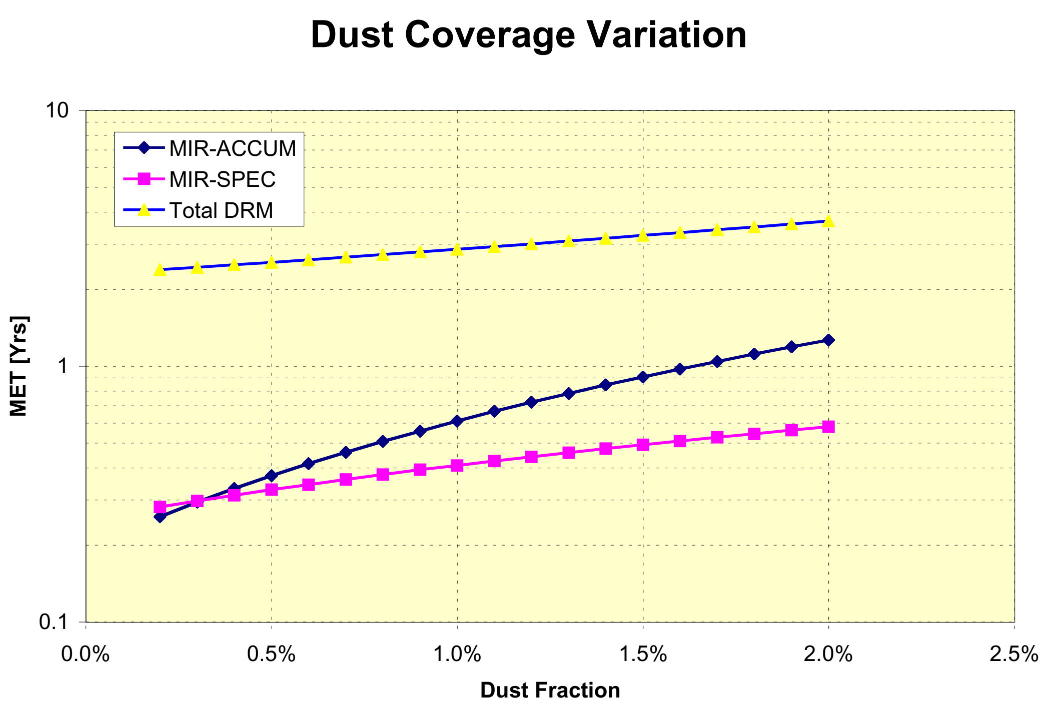


Fig. 14: Effect of dust on the primary and secondary mirrors. MIR images are most strongly affected. The Yardstick value is 1%.

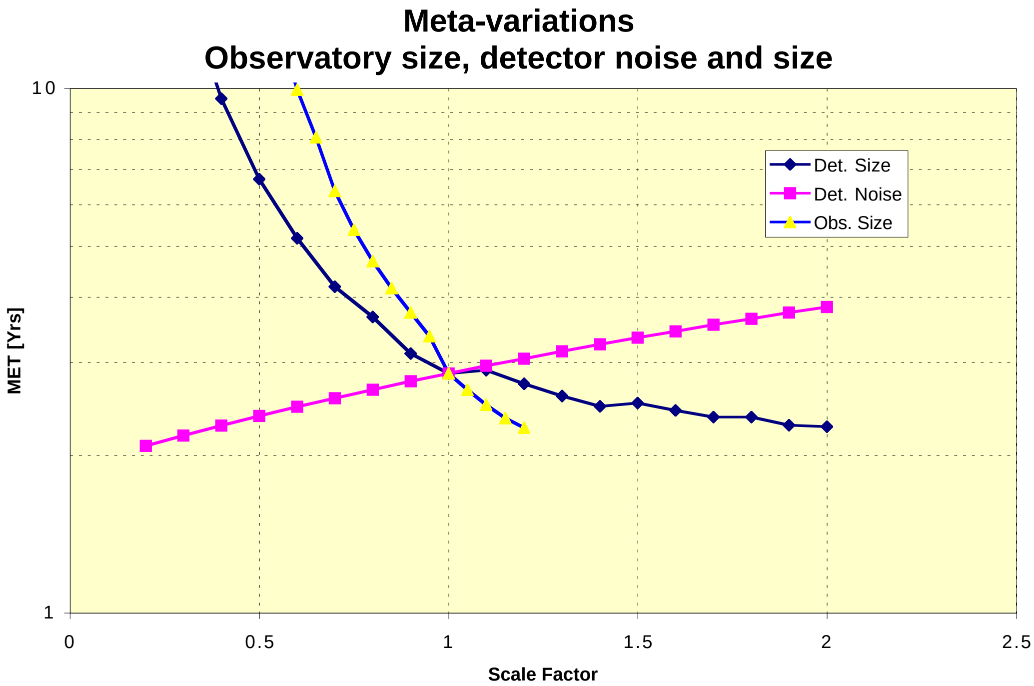


Fig. 15: Three multi-parameter (meta-) variations. Detector size is the number of pixels per side. Dark current and readout noise comprise detector noise. Observatory size is measured by its linear dimensions.

The sensitivity of the mission duration (MET) of the ASWG DRM to small variations of the design parameters in the vicinty of the Yardstick Design is shown in Table 3. The mission duration comprises exposure time and the overheads identified in Table 2 (*e.g.*, slew time, instrument setup, and detector readout). The sensitivity is measured in terms of the logarithmic derivative, $d\log(MET/MET_0)/d\log(p/p_0)$, which is tablulated as 'slope' in Table 3. Only the portion of the ASWG DRM affected by the given detector, or science instrument module contributes to the individual values of the mission duration, MET. Slopes greater than 1 are coded **red**, and slopes between 0.5 and 1.0 are coded **blue**.

Table 3: Sensitivity to single parameter variations

Parameter	Slope
Detector	
InSb Dark Current	0.24
InSb Max. integration time	-0.33
InSb Readout noise per read	0.40
InSb Well depth	0.00
Si:As Dark Current	0.15
Si:As Max. integration time	-0.01
Si:As Readout noise per read	0.00
Si:As Well depth	-0.19
Science Instrument Modules	
MIR-ACCUM FOV	**-0.58**
MIR-ACCUM Pixel Read Time	0.29
MIR-ACCUM Pixels/MUX	0.29
MIR-ACCUM Reads/frame	0.29
MIR-ACCUM Sky View	0.18
MIR-SPEC FOV	**0.61**
MIR-SPEC Pixel Read Time	0.05
MIR-SPEC Pixels/MUX	0.05
MIR-SPEC Reads/frame	0.05
MIR-SPEC Sky View	**-0.72**
NIR-ACCUM FOV	0.32
NIR-ACCUM Pixel Read Time	0.15
NIR-ACCUM Pixels/MUX	0.15
NIR-ACCUM Reads/frame	0.15
NIR-ACCUM Sky View	**-1.62**

Parameter	Slope
NIR-SPEC FOV	**1.64**
NIR-SPEC Multiplex factor	**-0.73**
NIR-SPEC Pixel Read Time	0.14
NIR-SPEC Pixels/MUX	0.14
NIR-SPEC Reads/frame	0.14
NIR-SPEC Sky View	**-2.24**
OPT-ACCUM FOV	0.32
OPT-ACCUM Pixel Read Time	0.13
OPT-ACCUM Pixels/MUX	0.13
OPT-ACCUM Reads/frame	0.13
OPT-ACCUM Sky View	**-1.12**
Spacecraft and OTA	
Primary Temperature	0.29
Secondary Temperature	0.01
Shield Area	0.24
Shield Emmissivity	0.24
Dust Coverage	0.24
Overheads	
Coarse track overhead	0.00
Fine track overhead	0.03
Major Slew Settling Time	0.01
Major slew time	0.03
Minor slew settling time	0.01
Minor Slew Time	0.01
SI setup time/exposure	0.00
Spectral Element Setup Time	0.01
Meta-variations	
Observatory size	-2.09
Detector size	**-0.66**
Detector noise	0.33

Orbit Variations

We investigated possible low-background orbits as a means of reducing the required telescope collecting area. Elliptical orbits with aphelia in the outer Solar System and inclined orbits that would take NGST above the interplanetary dust in the ecliptic plane were considered. For each orbit, the OTA and sunshield were scaled homologously, retaining critical sampling of the point spread function, but otherwise the Yardstick ISIM was retained. Two values (baseline and 10% of baseline) of the detector noise (dark current and effective readout noise current) were considered. The results are given in Table 4, in which the observatory scale factor for which the Ad Hoc Science Working Group reference science program would be completed in 2.5 years is given. The variation of required mission duration is given as a function of observatory scale factor in Figures 16 and 17.

Table 4: Obs. scale factor for a 2.5-yr mission

Orbit	Det. Noise = 10% Yardstick	Det. Noise = Yardstick
L2 Halo	0.88	1.10
Circular, 1 AU, i = 0˚, Ω = 0˚	0.89	1.11
Circular, 1 AU, i = 10˚, Ω = 0˚	0.83	1.04
Circular, 1 AU, i = 20˚, Ω = 0˚	0.76	0.99
Circular, 1 AU, i = 30˚, Ω = 0˚	0.73	0.98
Circular, 1 AU, i = 30˚, Ω = 45˚	0.71	0.97
Circular, 1 AU, i = 30˚, Ω = 90˚	0.71	0.97
Circular, 1 AU, i = 30˚, Ω = 135˚	0.70	0.97
Circular, 1 AU, i = 30˚, Ω = 180˚	0.71	0.97
Circular, 1 AU, i = 30˚, Ω = 225˚	0.71	0.97
Circular, 1 AU, i = 30˚, Ω = 270˚	0.72	0.98
Circular, 1 AU, i = 30˚, Ω = 315˚	0.71	0.97
Elliptical, 1x2 AU, ω = 0˚	0.59	0.86
Elliptical, 1x3 AU, ω = 0˚	0.53	0.82
Elliptical, 1x3 AU, ω = 45˚	0.52	0.81
Elliptical, 1x3 AU, ω = 90˚	0.54	0.82
Elliptical, 1x3 AU, ω = 135˚	0.55	0.83
Elliptical, 1x3 AU, ω = 180˚	0.56	0.83
Elliptical, 1x3 AU, ω = 225˚	0.52	0.81
Elliptical, 1x3 AU, ω = 270˚	0.52	0.81
Elliptical, 1x3 AU, ω = 315˚	0.52	0.81
Elliptical, 1x4 AU, ω = 0˚	0.51	0.80

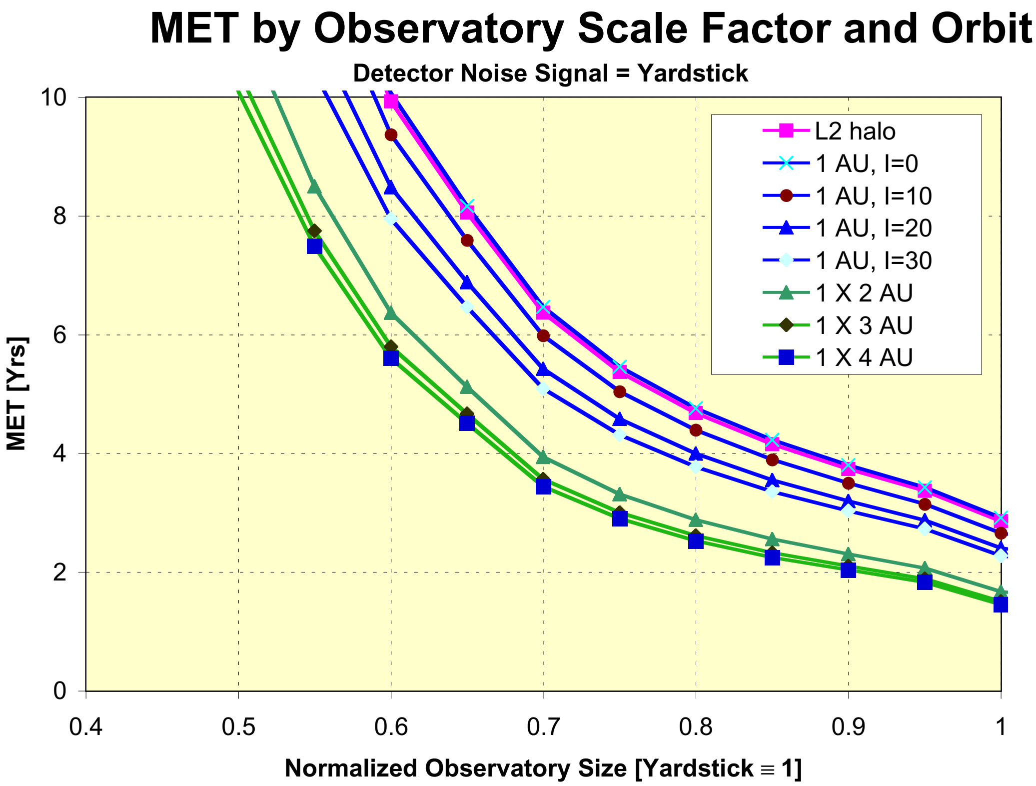
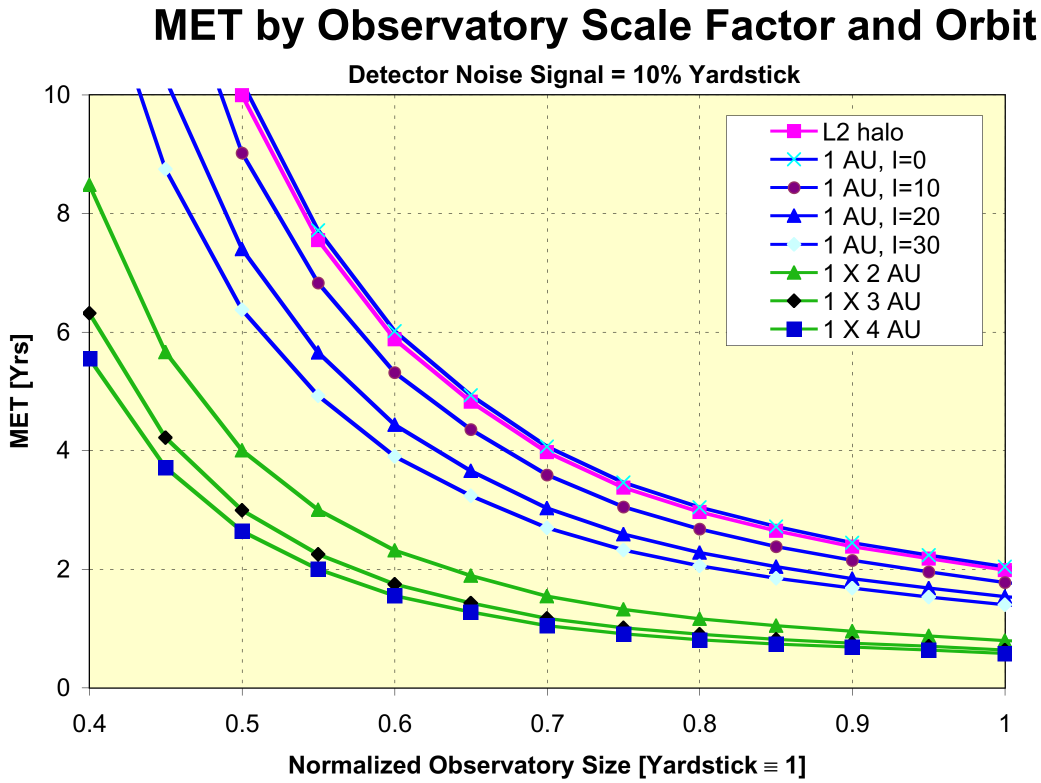


Fig. 16: Effect of orbit selection, for baseline detector noise. Circular orbits have $\Omega = 0^\circ$, elliptical, $\omega = 0^\circ$. The elliptical orbits provide greater advantage than inclined (30˚, or less) 1 AU orbits.

Fig. 17: Effect of orbit selection, for detector noise 10% of baseline. Circular orbits have $\Omega = 0^{\circ}$, elliptical, $\omega = 0^{\circ}$. The elliptical orbits provide greater advantage than inclined (30˚, or less) 1 AU orbits.



Conclusions

In this first investigation we have considered mostly variations of single parameters. These conclusions should be tempered by the realization that true design variations would likely involve more than one of the parameters that we've considered. Nevertheless, the following conclusions can be drawn from this investigation.

- The global variation of most parameters can be characterized simply by the slope of the logarithmic derivative of the MET. The exceptions are:
  - ♦ Mirror temperature, which causes a sharp increase (Fig. 13).
  - ♦ Detector plate scale and number of pixels, which have global minima (Fig. 3 and 4).
- The most sensitive parameters are those of the science instrument modules, and the size of the observatory (Table 3).
  - ♦ The most important instrument parameters are the plate scale of the NIR camera and spectrometer.
  - ♦ Next in importance are the plate scale of the MIR spectrometer; the number of pixels of the detectors for the MIR camera and spectrometer, and NIR spectrometer; and the multiplex limit of the NIR spectrometer.
- Observing overheads (slewing, acquisition, readout, instrument motions) are relatively unimportant due to their relatively small values (Table 1 and Table 3).
- The field of regard is a relatively unimportant determinant of mission duration (Fig. 11).
- The large elliptical orbits (2 - 4 AU aphelia) provide more benefit than inclined orbits (up to 30˚)
- A reduced detector noise, L2 mission is:
  - ♦ Better than an inclined orbit with Yardstick noise
  - ♦ Equal to a 1 X 2 AU orbit with Yardstick noise
  - ♦ Comparable to a 1 X 3 AU orbit with Yardstick noise
- A 1 X 3 AU, reduced noise mission would require an OTA one-half the size of the Yardstick Design.